REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
20-04-2004

2. REPORT TYPE
REPRINT

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Ionospheric patch formation: Direct measurements of the origin of a polar cap patch

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
2311

5e. TASK NUMBER
SD

5f. WORK UNIT NUMBER
A4

6. AUTHOR(S)
Herbert C. Carlson, Jr.*, Kjellmar Oksavik**, Joran Moen**,
Todd Pedersen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory/VSBXI
29 Randolph Road
Hanscom AFB, MA 01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-VS-HA-TR-2005-1072

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/VSBXI

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
REPRINTED FROM: Geophysical Reesearch Letters, Vol. 31, L08806, doi:10.1029/2003GL019166, 2004. Copyright 2004, American Geophysical Union. *Air Force Office of Scientific Research, Arlington, VA (continued)

14. ABSTRACT
We present the first direct measurements documenting the origin of an ionospheric patch, emerging into the polar cap from the noon dark cusp region of the dayside auroral oval. A series of such patches were observed. The observed patch-formation signatures, in plasma density and velocity, ion and electron temperature, and optical transient signatures, are all compared to those required of the Lockwood andCarlson [1992] transient reconnection mecchanism for patch formation. Conformity of the observed signatures, to the stringent signatures demanded of these five ilndependent parameters by the tested mechanism, is taken as strong substantiation of the applicability of this mechanism. The data exclude two alternate candidate mechanisms.

15. SUBJECT TERMS
Polar ionosphere
Auroral cusp
Incoherent scatter radar
Polar cap patches

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCL	UNCL	UNCL	UNL		Todd R. Pedersen
					19b. TELEPHONE NUMBER *(Include area code)* (781) 377-2845

Block 13 (Continued)

**Physics Department, University of Oslo, Blindern, Norway

AFRL-VS-HA-TR-2005-1072

GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L08806, doi:10.1029/2003GL018166, 2004

Ionospheric patch formation: Direct measurements of the origin of a polar cap patch

Herbert C. Carlson Jr.,[1] Kjellmar Oksavik,[2] Joran Moen,[2] and Todd Pedersen[3]

Received 14 July 2003; revised 3 March 2004; accepted 12 March 2004; published 20 April 2004.

[1] We present the first direct measurements documenting the origin of an ionospheric patch, emerging into the polar cap from the noon dark cusp region of the dayside auroral oval. A series of such patches were observed. The observed patch-formation signatures, in plasma density and velocity, ion and electron temperature, and optical transient signatures, are all compared to those required of the *Lockwood and Carlson* [1992] transient reconnection mechanism for patch formation. Conformity of the observed signatures, to the stringent signatures demanded of these five independent parameters by the tested mechanism, is taken as strong substantiation of the applicability of this mechanism. The data excludes two alternate candidate mechanisms. *INDEX TERMS:* 2431 Ionosphere: Ionosphere/magnetosphere interactions (2736); 2463 Ionosphere: Plasma convection; 2467 Ionosphere: Plasma temperature and density; 2475 Ionosphere: Polar cap ionosphere; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers. **Citation:** Carlson, H. C., Jr., K. Oksavik, J. Moen, and T. Pedersen (2004), Ionospheric patch formation: Direct measurements of the origin of a polar cap patch, *Geophys. Res. Lett.*, *31*, L08806, doi:10.1029/2003GL018166.

1. Introduction

[2] For southward interplanetary magnetic field (IMF negative) conditions, which apply half the time, the character of the polar cap ionosphere is dominated by the presence of F region patches. Patches are islands of high plasma density, comparable to daytime mid-latitude values, surrounded by much lower plasma densities characteristic of nighttime values. While the properties of these patches have been studied for twenty years [*Weber et al.*, 1984; *Anderson et al.*, 1988; *Carlson*, 1994; *Crowley*, 1996; *Basu and Valladares*, 1999], we still do not know their dominant formation mechanism(s). Adequate measurements have been absent. Such understanding, beyond being of intrinsic interest to ionospheric and plasma physics, is of practical application to prediction of communication and navigation disruption at high latitudes [*Buchau et al.*, 1985; *Basu and Valladares*, 1999]. Here we present the first observations of a patch at its moment of creation. These are furthermore the first sufficiently definitive maps of transient patch formation to rigorously test for the patch production mechanism. First we describe below specific signatures in five independent physical parameters, all required by the *Lockwood and Carlson* [1992] transient reconnection mechanism for patch creation. Then we test for the presence or absence of each of these predicted signatures. Absence of one or more would prove the mechanism inapplicable. The presence of all would have to be taken as very strong support of the mechanism for patch production, as well as for the presence of the physical processes on which it is based, and phenomena which logically follow.

2. Signatures for Critical Test

[3] The *Lockwood and Carlson* [1992] mechanism is based on a burst of magnetopause reconnection, which applies a voltage (in its own rest frame) along the X-line in the low-latitude magnetopause. This voltage projects down to the ionosphere where (absent of any significant field-aligned voltage drop) it applies to the merging gap in its own rest frame (Figure 1). The flux transferred across the boundary, in the earth's frame, can occur by either having the merging gap move equatorward, or be fixed in the earth frame with a poleward flow of ionospheric plasma through it, or both. In the latter case, when there is no reconnection there is no voltage and thus no plasma flow in the dayside ionosphere between reconnection pulses (assuming no other sources of flow), so a continuous tongue of plasma enters the polar cap. In the former case, at the onset of reconnection the merging gap migrates towards the equator, crossing plasma whose flow into the polar cap accelerates with time during the reconnection. This boundary migration can bring in increasingly higher density plasma as the boundary moves increasingly equatorward. At turnoff (when reconnection stops there is zero electric field along the merging gap) the plasma flows poleward with the merging gap boundary, as the open-closed boundary relaxes back poleward toward an equilibrium configuration [*Cowley and Lockwood*, 1992]. Near the day/night terminator, one can see that this brings low density plasma in behind the higher density plasma, thereby "pinching off" the high plasma density patch by the time the flows have stopped (Figure 2).

[4] Stated more generally, patches occur because adjacent flux tubes in the polar cap have arrived via different paths, and patches can originate from significantly different locations outside or inside the polar cap (e.g., sunlit sub-auroral, trough, dark polar cap, etc.). However, it is most convincing to test this mechanism when the merging gap is slightly poleward of the day/night terminator. Then this alternation of high vs. low density plasma can be an unambiguous indicator.

[5] Several signatures then must follow. Each time we identify a unique signature that can be experimentally tested, we will denote it by a number {x}, for reference in the Discussion of Data section, where we will search for

[1]Air Force Office of Scientific Research, Arlington, Virginia, USA.
[2]Physics Department, University of Oslo, Blindern, Norway.
[3]Air Force Research Laboratory, Space Vehicles Directorate, Hanscom Air Force Base, Massachusetts, USA.

0094-8276/04/2003GL018166$05.00

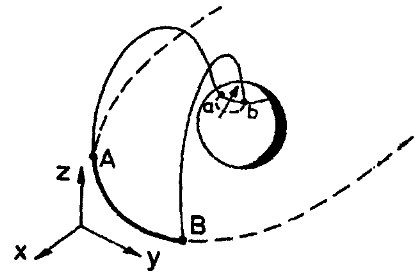

Figure 1. Projection of magnetopause reconnection X-line (AB) to ionospheric merging gap (ab), adapted from *Cowley and Lockwood* [1992].

each signature. The absence of any one disqualifies applicability of the mechanism.

[6] When Southward IMF conditions apply, near local magnetic noon, one should look just poleward of the cusp, for F region peak plasma densities that alternate between high and low values, entering the polar cap from the cusp. This will be the signature of patches having been formed. The envelope of the high density plasma regions (patches) should move stepwise poleward {1}, with time resolutions of about two minutes required to follow events. Plasma velocity V_i boundary leaps {2} must coincide in time and space with the virtual motion of the high density plasma N_e contours, ramping up in a couple of minutes, and lasting a few minutes. Right after reconnection, the magnetic curvature or tension forces drive the plasma dawnward and westward for IMF By > 0 (duskward and eastward for By < 0) as in Figure 2, thereby defining the sense of the velocity flow burst. This drags the plasma through the thermosphere below, leading to ion heating, as the downward Poynting flux energy is dissipated in frictional drag or ohmic heating. The ion temperature T_i {3} enhancement serves as a sensitive indicator, as a few-minute integration over spurts or shears in V_i.

[7] The reconnection event will also initially dump trapped particles into the ionosphere and thermosphere. This will cause an initial flash {5} of optical emissions in the green (the faster precipitated energetic electrons) and red lines. The flash should last a few of minutes (time to precipitate energetic particles), and just precede (timing of {5} wrt {1, 2, 3}) the onset of the reconnection velocity shear. This is because the precipitated energetic electrons take significantly less time to reach the thermosphere than the Alfven waves, which take a couple of minutes to communicate to the ionosphere the new motion it must assume after reconnection. Energetic particles will initially precipitate out the feet of the newly reconnected magnetic flux tubes as they transport downstream from the sun.

[8] The electrons precipitated by the newly opened field lines will also heat the ambient electron gas that they transit downwards, to the ionosphere and thermospheric heat sink, increasing the electron temperature T_e {4}. The heating and cooling time constant for the T_e response is about 30 seconds, so T_e increases only during the time required for the particles to dump out of the flux tube, disappearing thereafter with a half minute cooling decay time. The electron gas has so little heat capacity though, that many other heating and cooling phenomena enter into its overall thermal balance, so signs of a transient heat input are necessary, but are not an unambiguous signature.

[9] A current sheet must be initiated with the reconnection event for magnetic field topology-preservation, separating different particle populations. Associated soft-electron aurora poleward (equatorward) of the velocity shear for IMF By > 0 (By < 0) and faster electron excitation are not pursued here, as we had no optical data from Svalbard.

[10] In summary, each N_e contour motion, coincident with a true V_i spurt, of a B_y dependent sense of east/west motion, should be accompanied by a spurt of T_i enhancement, all coincident in time and space {1, 2, and 3 coincident}. Each of these transients must be synchronized with each reconnection event. Enhanced T_e is necessary {4} but not sufficient proof. However we can look for a clear optical signature as an immediate precursor to the plasma motion. Upon the reconnection event, these optical emissions, excited by initially dumped particles, should show as a flash at the feet of the newly opened field lines. Within the cusp the flash should only last a few minutes, initially brightening, broadening, and fading.

3. Observing Mode

[11] We now discuss the observing mode used to search for these critical signatures in the plasma parameters {1}, {2}, {3}, and {4}. Although the mechanism we test here was hypothesized in 1992, it was not until now, a decade later, that an observing mode could be created to test it. The doubled ESR transmitter power, plus our new radar controller and analysis methods, enabled us to invent a capability to sample 1200 km by 600 km areas, yet revisit a given piece of plasma every two minutes in a windshield wiper mode. This enabled study of new classes of space plasma processes. *Carlson et al.* [2002] introduced this new high-speed mesoscale mapping capability, and illustrated its comprehensive accuracy mapping full thermal plasma properties of a cold "fossil" patch well inside the polar cap, downstream from the presumed region of origin.

[12] By contrast, here we observe the actual process of creation of a patch, and trace it emerging from the cusp as

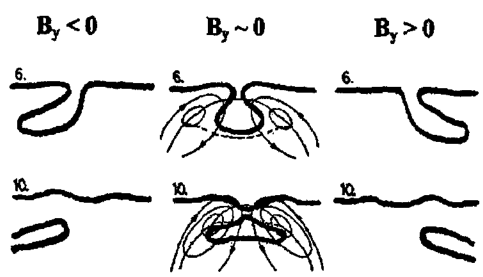

Figure 2. Snapshots of ionospheric flow 6 and 10 (~2 minute) time steps into a sequence of reconnection pulses [*Carlson*, 2003; after *Lockwood and Carlson*, 1992] where the merging gap, having migrated equatorward is seen (6) almost relaxed back to it's starting position (thin arch), and later (10) starting it's next pulse cycle. The heavy line is a high-density plasma contour, initially straight east-west, and dashed line the initial merging gap. Arrows trace plasma flow, poleward is up.

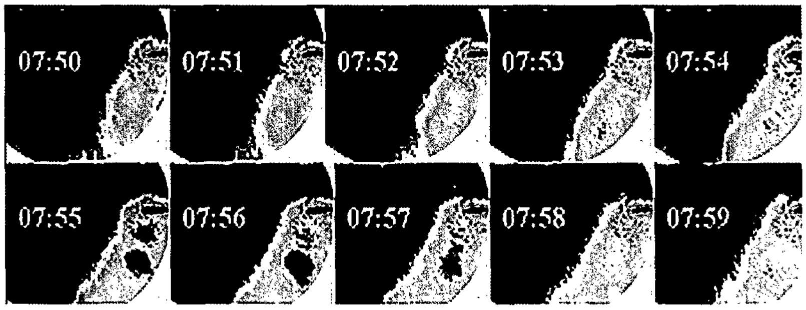

Figure 3. The 4 plasma parameters measured by the ESR, in a magnetic meridian plane spanning ~1200 km north-south, by 600 km altitude, just before and just after the reconnection event. Magnetic north, about 40° west of geographic north, points towards Nord, Greenland. The patch formation event is most noticeable overhead to 200 km North.

it enters the polar cap, still hot from the initial transient heating of formation. These data allow for the first time, rigorous test of alternate competing patch production mechanisms.

[13] Data is taken with the single fully steerable ESR antenna, at a fixed azimuth, windshield wiping the radar elevation from 30° above the northern horizon, through zenith, to 30° above the southern horizon, and back. Other than that, data is taken as by *Carlson et al.* [2002], with each mapped cell measured with a 3.2 second and 50 km range resolution, and 128 s per sweep.

4. Discussion of Data

[14] During 07:40–08:30 UT (~10:30–11:20 MLT), on January 20, 2001, four regions of enhanced N_e were observed to emerge poleward from the cusp region, and could be tracked moving 600 km into the polar cap before leaving the field of view (FOV) of the ESR. The location of the cusp persisted between overhead and 200 km south of the ESR, where we define the cusp location by the signatures of persistently enhanced N_e, T_e and T_i, and V_i shear boundaries. This persistence was periodically interrupted by poleward surges of all these boundaries coincident with poleward launching of enhanced N_e regions (patches).

[15] Figure 3 shows the four plasma parameters directly measured by the ESR: N_e, T_e, T_i, and V_i, for two consecutive sampling periods with a full latitude sweep every 128 seconds. The data set starting 07:55:52 UT (10:45 MLT) shows two patches centered about 300 and 500 km north of overhead, formed during the previous 15 minutes. The next data set, starting 07:57:52 UT shows the initial emergence of a new (third) patch from the cusp region.

[16] Now examine the details of the plasma properties during this transient patch-formation time. The poleward surge of a high N_e contour defines the envelope of the entering patch {1}. From 07:57 to 07:59 the poleward edge of this high N_e boundary goes from overhead to about 100 km northward (15° north of vertical). At the same time the location of the V_i boundary, from >150 m/s away to towards or stagnant, shows the very same movement (from overhead to 100 km northward) in the F region {2}. At 07:55 the poleward edge of the cusp coincides with the poleward edge of the enhanced Ti, taken as noted above as a boundary between two different plasma populations. At 07:57, while this boundary remains, an additional T_i boundary is seen, about 100 km north of overhead. This boundary also is coincident with the poleward edge of the high N_e and new V_i boundary location {3}.

[17] At 07:55 T_e above 300 km is persistently near 3000 K in a 200 km wide latitude band from overhead to about 200 km equatorward, with lower T_e outside this band. At 07:57 this high T_e band has moved 100 km poleward {4}, in synchronism with the location and timing of the poleward shift of the N_e, T_i, and V_i boundaries just noted. Recall the electron gas is too tenuous for T_e to be an unambiguous boundary signature, but this motion is entirely consistent with our hypothesis.

[18] For the fifth signature predicted, Figure 4 shows ASIP data from Nord which includes the cusp and poleward ESR FOV in its magnetically southern FOV. Images are shown at one-minute intervals during the ten-minutes of 07:50–07:59 UT. There is one flash of 630.0 nm emission seen in the cusp, from 07:55–07:57. This is just the precursor timing required of the hypothesized mechanism

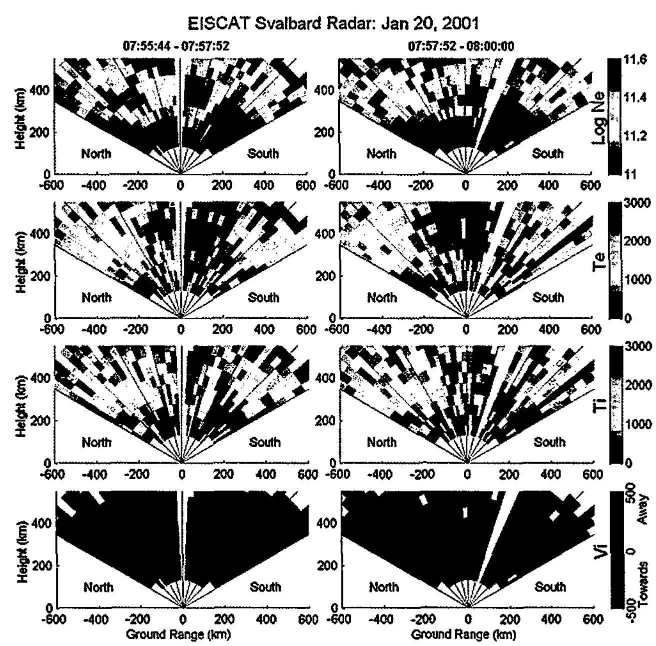

Figure 4. All sky photometric (ASIP) images for the F-region field of view from Nord. The cusp over Svalbard is in the lower right, showing a transient 630.0 nm flash in 1 minute frames, at the reconnection event time (fixed red streak is artifact).

we are testing against the observations here {5}. To rule out chance coincidence, we note that during the full time from 07:40–08:30, only 4 such flashes were seen, each coinciding within the 1–2 minute time resolution of the data, with launching of a new patch from the cusp into the polar cap.

[19] Thus, all five signatures required by the *Lockwood and Carlson* [1992] patch formation mechanism are observed, including stringent temporal and spatial relationships. N_e, V_i, T_i, and the optical flash show verification, and T_e shows the required consistency. This is taken as rather remarkable agreement with, or confirmation of, the model tested.

[20] We can also rule out two alternate patch generation mechanisms here. One is segmentation of a continuous tongue of ionization through the cusp, by enhanced chemical recombination in a high velocity plasma jet. Here we observe increased plasma density in high velocity streams away from the cusp (carrying the high density plasma into the polar cap), not decreased density. This rules out that mechanism here. Plasma flows much greater than $\sim$1 km/s should erode plasma at altitudes much below 250 km (the plasma densities here peak near and above 300 km) and so should play some role for patches from the lower altitude sunlit cusp at Sondrestrom [*Valladares et al.*, 1996]; however, not here. We can also exclude production of these patches within the polar cap by cusp particle precipitation [*Walker et al.*, 1999]. Scaling the calculations of *Millward et al.* [1999] as done by *Nielsen et al.* [2004], to the two minute duration of particle bursts observed here, we calculate a particle precipitation enhancement of $<0.5\ 10^{11}\ m^3$ above the background, only about 15% of the observed $\sim 3\ 10^{11}\ m^3$ enhancement. The plasma enhancements inserted poleward of the cusp here must then be due to transport of higher density plasma from outside the polar cap. Long duration ($\sim$10 min) cusp particle precipitation could produce low-to-moderate, but not high density ($10^{12}\ m^3$) patches [*Nielsen et al.*, 2004].

5. Conclusions

[21] In this paper we have presented the first data of time resolution, spatial coverage, and accuracy adequate to meaningfully test for the mechanism producing ionospheric polar cap patches. The data covers a $\sim$600 by 1200 km area in the magnetic meridian plane spanning the dark noon cusp, with $\sim$2 minute time resolution for several hours about magnetic noon. Under southward IMF conditions we observed a sequence of high N_e regions emerge from the cusp location and move antisunward (poleward) into the polar cap.

[22] Five transient signatures are identified that must be present during the initiation of these moving density enhancements, if these patches are indeed produced by the *Lockwood and Carlson* [1992] mechanism of transient reconnection. Failure of any one would disqualify the mechanism proposed. We see all five signatures (N_e, V_i, T_i, T_e, and optical emission flashes), with the predicted relative timing and locations. The observations here also exclude explanation by an alternate mechanism, segmentation of a plasma tongue by enhanced recombination in velocity jets. The transients are of too short duration for particle precipitation to contribute significantly to creating these patches within the polar cap. Digisonde data verifies patch signatures present later in the central polar cap.

[23] We present these data as compelling evidence for the *Lockwood and Carlson* [1992] patch generation mechanism to apply to the series of patches seen on this day. We also take these data then to be strong evidence for the applicability of the more fundamental plasma processes on which this mechanism for patch production is premised. Lastly, we demonstrate plasma processes essential to the fundamental nature of the polar ionosphere and its coupling to the solar wind, which intrinsically derive from events of a transient nature. The gross behavior of the associated circulation can then partially be the sum of many such transient events.

[24] **Acknowledgments.** We are happy to acknowledge support from AFOSR 2311 AS and the Norwegian Research Council. Thanks to staff on EISCAT Svalbard Radar. EISCAT is an International Association supported by Finland (SA), France (CNRS), the Federal Republic of Germany (MPG), Japan (NIPR), Norway (NFR), Sweden (NFR) and the United Kingdom (PPARC).

References

Anderson, D. N., et al. (1988), Origin of density enhancements in the winter polar cap ionosphere, *Radio Sci.*, *23*, 513.

Buchau, J., et al. (1985), Ionospheric structures in the polar cap: Their origin and relation to 250-MHz scintillation, *Radio Sci.*, *20*, 325.

Basu, S., and C. Valladares (1999), Global aspects of plasma structures, *J. Atmos. Solar Terr. Phys.*, *61*, 127.

Carlson, H. C. (1994), The dark polar ionosphere: Progress and future challenges, *Radio Sci.*, *29*, 157.

Carlson, H. C. (2003), A voyage of discovery into the polar cap and Svalbard, in *Egeland Symposium of Atmospheric and Auroral Research*, edited by J. Moen and J. A. Holtet, Norwegian Academy of Science Press, Oslo, Norway, pp. 33–53.

Carlson, H. C., et al. (2002), ESR mapping of polar-cap patches in the dark cusp, *Geophys. Res. Lett.*, *29*(10), 1386, doi:10.1029/2001GL014087.

Cowley, S. W. H., and M. Lockwood (1992), Excitation and decay of solar-wind-driven flows in the magnetosphere-ionosphere system, *Ann. Geophys.*, *10*, 103.

Crowley, G. (1996), Critical review of ionospheric patches and blobs, *Review of Radio Science* 1993–1996, edited by W. R. Stone, pp. 619–648, Oxford Univ. Press, New York.

Lockwood, M., and H. C. Carlson (1992), Production of polar cap electron density patches by transient magnetopause reconnection, *Geophys. Res. Lett.*, *19*, 1731.

Millward, G. H., et al. (1999), Modeling of ionospheric effects of ion and electron precipitation in the cusp, *J. Geophys. Res.*, *104*, 2460.

Nielsen, C. P., et al. (2004), Patch formation in relation to cusp auroral activity, *Ann. Geophys.*, in press.

Valladares, C. E., et al. (1996), Modeling the formation of polar cap patches using large plasma flows, *Radio Sci.*, *31*, 573.

Walker, I. K., et al. (1999), On the possible role of cusp/cleft precipitation in the formation of polar-cap patches, *Ann. Geophys.*, *17*, 1298–1305.

Weber, E. J., et al. (1984), F-layer ionization patches in the polar cap, *J. Geophys. Res.*, *89*, 1683.

H. C. Carlson Jr., Air Force Office of Scientific Research, 801 N. Randolph Street, Mail Room 732, Arlington, VA 22203-1977, USA. (herb.carlson@afosr.af.mil)

J. Moen and K. Oksavik, Physics Department, University of Oslo, P.O. Box 1048, N-0316 Blindern, Norway.

T. Pedersen, Air Force Research Laboratory, Space Vehicles Directorate, 29 Randolph Road, Hanscom Air Force Base, MA 01731-3010, USA.